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High Altitude Limit of the Gradient Drift Instability

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ERRATA

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Form 1473, Block 20, last line $\upsilon_{in} >> 4cE_o/BL$ should read $\upsilon_{in} << 4cE_o/BL$

Pg. 5, last paragraph, 4th line $\gamma = 0.1\ cE_o/BL$, i.e., one-tenth should read $\gamma = 0.1\ (cE_o/BL)^{1/2}$, i.e., 70%

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The gradient drift instability for F region plasma clouds is investigated retaining ion inertia effects. Using the assumption that the ion gyrofrequency, Ω, is greater than ion inertial time changes $(\partial/\partial t + V_i \cdot \nabla)$ and the ion-neutral collision frequency ν_{in}, a quadratic dispersion equation results. In the limit that $\nu_{in} >> 4cE_o/BL$ (E_o and B are the ambient electric and magnetic fields, and L is the plasma cloud density gradient scale length), the growth rate, γ, reduces to the usual result cE_o/BL. In the opposite limit $\nu_{in} \lessapprox 4cE_o/BL$, $\gamma = (cE_o \nu_{in}/BL)^{1/2}$. This result can explain

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20. Abstract (Continued)

why high altitude (~ 450 km) barium releases, where ν_{in} is less than unity and a factor of 10-100 smaller than at lower altitudes (~ 200 km), striate on time scales similar to the lower altitude releases.

CONTENTS

HIGH ALTITUDE LIMIT OF THE GRADIENT DRIFT INSTABILITY

I. INTRODUCTION

The $\underline{E} \times \underline{B}$ gradient drift instability (Simon, 1963) has been used to explain striation formation in plasma clouds (Linson and Workman, 1970; Volk and Haerendel, 1971) released in the ionosphere at altitudes ≤ 250 km. Nonlinear computer simulation studies of this instability (Scannapieco et al., 1976; Doles et al., 1976) have done well in reproducing the evolution of plasma cloud striations at late times (comparison of numerical simulation plots with photographs of striated barium clouds show many simularities).

In investigation of the $\underline{E} \times \underline{B}$ instability in the previously referenced works, ion inertia has been neglected, i.e., in the ion momentum equation $\partial/\partial t + \underline{V}_i \cdot \nabla \ll \nu_{in}$, where ν_{in} is the ion-neutral collision frequency. This approximation, valid for barium cloud releases in the 200 km altitude range, allows for the simple algebraic solution of the ion velocity as a function of the electric and magnetic fields. In the simplest one level, two dimensional electrostatic plasma cloud model one then has two equations. One is a continuity equation for the electron density and the other is a potential equation resulting from the divergence of the current equalling zero. Linearizing these equations, in a slab geometry, yields for the growth rate, at F region altitudes, $\gamma = cE_o/BL$ where c is the speed of light, L is the plasma density gradient scale length in the cloud, and E_o and B are the ambient electric and magnetic fields, respectively. This growth rate is deceptive for it apparently has no ν_{in} dependence and therefore seems altitude independent. Closer inspection of the equations shows that for $\nu_{in} = 0$, $\gamma = 0$. Indeed, the $\underline{E} \times \underline{B}$ gradient drift instability is dependent upon having a current perpendicular to the plasma cloud density gradient and both in turn are perpendicular to the ambient magnetic field. In the case of F region plasma clouds the current is provided by the Pedersen drift of the ions, which is $\propto \nu_{in}/\Omega$ (Ω is the ion gyrofrequency) for $\nu_{in}/\Omega \ll 1$.

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At very high altitudes this ion Pederson drift becomes exceedingly small. Consequently, one might think that the gradient drift instability is inoperative. Contrary to this thought, barium clouds released at altitudes ~ 450 km exhibit striation formation (Pongratz and Jeffries, 1977; also M. Pongratz, private communication, 1977) just about as fast as those released in the 200 km altitude regime. The basic question is: how is this possible within the context of the gradient drift instability regime? The answer to this question resides in keeping ion inertia terms (at high altitudes these terms are not small compared with ν_{in}).

Linson and Workman (1970) mentioned the effects of ion inertia very briefly. They noted that keeping these terms resulted in a complicated cubic dispersion relation and at altitudes ~ 200 km did not change the usual growth rate results. However, in the present note, we show that at high altitudes $\gamma \approx (cE_o \nu_{in}/BL)^{\frac{1}{2}}$, valid for $cE_o/BL \gg \nu_{in}$. Because ν_{in} enters as the square root, a factor of 10-100 decrease in ν_{in} still produces reasonable growth rates compared with the usual cE_o/BL growth rate. In section II, we give the theory and section III contains a discussion and summary.

II. THEORY

The basic set of equations we use for ions and electrons are as follows:

$$\frac{\partial n_e}{\partial t} + \nabla\cdot(n_e \underline{V}_e) = 0 \tag{1}$$

$$\frac{\partial n_i}{\partial t} + \nabla\cdot(n_i \underline{V}_i) = 0 \tag{2}$$

$$\underline{V}_e = \frac{-c}{B^2} \nabla \varphi \times \underline{B} \tag{3}$$

$$M\left(\frac{\partial \underline{V}_i}{\partial t} + \underline{V}_i\cdot\nabla\underline{V}_i\right) = e\left(\frac{\underline{V}_i}{c} \times \underline{B} - \nabla \varphi\right) - \nu_{in} \underline{V}_i \tag{4}$$

where subscripts e and i refer to electrons and ions; n the density; $\underline{V}$ velocity; $\underline{B}$ the magnetic field; the electric field $\underline{E} = -\nabla \varphi$; e the electronic charge; M the ion mass; and ν_{in} the ion-neutral collision frequency. In this study the temperature is being set equal to zero. Taking $n_e = n_i = n$, equations (1) and (2) yield the divergence of the current being zero

$$\nabla \cdot [n(\underline{V}_e - \underline{V}_i)] = 0 \tag{5}$$

We will choose a simple slab geometry such that $\underline{B} = B\hat{z}$ (B is constant), the ambient (zero order) electric field $\underline{E}_o = E_o\hat{x}$, and the plasma cloud density profile is $n_o = n_o(y)$. To determine the instability condition, we linearize the above set of equations such that

$$\begin{aligned} \underline{V}_i &= \underline{V}_{io} + \tilde{\underline{V}}_i e^{i(kx-\omega t)} \\ n &= n_o(y) + \tilde{n}\, e^{i(kx-\omega t)} \\ \varphi &= \varphi_o(x) + \tilde{\varphi}\, e^{i(kx-\omega t)} \end{aligned} \tag{6}$$

This yields the following determinant set of equations

$$\left(-i\omega + \nu_{in} + ikV_{iox} + \frac{\Omega^2}{(-i\omega+\nu_{in})}\right) \tilde{V}_{ix} + \frac{e}{M}\, ik\tilde{\varphi} = 0 \tag{7}$$

$$\left(-n_o ik + \frac{\Omega}{(-i\omega+\nu_{in})} \frac{\partial n_o}{\partial y}\right) \tilde{V}_{ix} + \frac{c}{B}\, ik \frac{\partial n_o}{\partial y} \tilde{\varphi} - V_{iox} ik\tilde{n} = 0 \tag{8}$$

$$\frac{c}{B}\, ik \frac{\partial n_o}{\partial y} \tilde{\varphi} - i\omega\tilde{n} = 0 \tag{9}$$

where $\Omega = eM/Bc$ is the ion gyrofrequency.

Equations (7), (8), and (9) essentially come from the ion momentum (eqn. (4)), the divergence of the current (eqn. (5)) and the electron continuity (eqn. (1)) equations, using equation (3). The subscript x refers to the x component, with $\tilde{V}_{iy}$ having been eliminated using the y component of the vector equation (4).

The usual striation growth rate limit is obtained by setting $-i\omega + ikV_{iox}$ equal to zero inside the parenthesis in eqn. (7) and setting denominators of the form $(-i\omega + \nu_{in})$ equal to ν_{in} in eqns. (7) and (8). These steps are equivalent to neglecting ion inertia in the ion momentum equation. Furthermore, one takes the F region limit $\nu_{in}/\Omega \ll 1$ and then we have from eqns. (7), (8), and (9)

$$\gamma = -V_{iox} \frac{\Omega}{\nu_{in}} \frac{1}{n_o} \frac{\partial n_o}{\partial y}$$

where $\omega = \omega_r + i\gamma$. Taking V_{iox}, the Pedersen ion drift to be $(cE_o/B)(\nu_{in}/\Omega)$ yields

$$\gamma = -\frac{c}{B} E_o \frac{1}{n_o} \frac{\partial n_o}{\partial y}$$

the usual $\underline{E} \times \underline{B}$ gradient drift growth rate (showing that only one side of a plasma cloud is linearly unstable). Setting $V_{iox} = 0$ in eqns. (7) and (8) yields no growth. If one takes the determinant of the coefficients of eqns. (7) - (9) one obtains a cubic equation for ω.

However, if the following assumption is made

$$\Omega \gg \omega, \underline{V}_i \cdot \nabla, \nu_{in} \tag{10}$$

then only the last term in the parenthesis multiplying $\tilde{V}_{ix}$ in eqn. (7) survives. This results in a quadratic equation for ω which yields for the growth rate

$$\gamma = \frac{1}{2} \nu_{in} + \frac{1}{2} \left(\nu_{in}^2 - 4 V_{iox} \Omega \frac{1}{n_o} \frac{\partial n_o}{\partial y}\right)^{\frac{1}{2}} \tag{11a}$$

Taking $V_{iox} = (cE_o/B)(\nu_{in}/\Omega)$ and identifying $-n_o(\partial n_o/\partial y)^{-1}$ with L, the plasma cloud density gradient scale length eqn. (11a) becomes

$$\gamma = -\frac{1}{2} \nu_{in} + \frac{1}{2} \left(\nu_{in}^2 + 4 \frac{c}{B} \frac{E_o \nu_{in}}{L}\right)^{\frac{1}{2}} \tag{11b}$$

Although V_{iox} is $\propto \nu_{in}/\Omega$ and therefore small, it is multiplied by a factor Ω in eqn. (11a) and so becomes important (i.e., finite but

small Pedersen currents are important). It should be noted that the result of (eqn. 11b) can be obtained from Ott's [1977] analysis of the Rayleigh-Taylor instability in dealing with equatorial Spread F by replacing g by $\nu_{in} E_o c/B$ in his eqn. (9a).

Equation (11b) represents the growth rate for an F region cloud where $\nu_{in}/\Omega \ll 1$ with the further assumptions given by (10). We can further break eqn. (11b) into two regimes. We obtain

$$\gamma \approx \begin{cases} \dfrac{c}{B}\dfrac{E_o}{L}, \text{ with } \nu_{in} \gg 4\,\dfrac{c}{B}\,\dfrac{E_o}{L} & (12a) \\[2ex] \left(\dfrac{c\,E_o}{BL}\,\nu_{in}\right)^{\frac{1}{2}}, \text{ with } \nu_{in} \ll \dfrac{4c\,E_o}{BL} & (12b) \end{cases}$$

Equation (12a) represents the usual $\underline{E} \times \underline{B}$ gradient drift instability for plasma clouds in ionosphere (Linson and Workman, 1970) and (12b) represents the high altitude limit.

III. DISCUSSION AND SUMMARY

In any case of interest the limits of validity are clearly defined in eqns. (12a) and (12b). The two regimes depend on ambient electric field conditions and the plasma cloud density gradient scale length, L. For a plasma cloud released around 200 km altitude with $L \sim 1$km, $E_o \sim 1$ mV/m and $B \sim 0.5$ gauss $4cE_o/BL \approx 0.08$ $\sec^{-1}$ whereas $\nu_{in} \sim 4 \sec^{-1}$ clearly showing the regime of (12a). Thus larger scale lengths certainly satisfy this criterion. In the above setting $E_o \sim 5$ mV/m yields that $4\,cE_o/BL \sim .4$ which is still a factor of ten smaller than ν_{in}. At the higher altitudes of 450-500 km $\nu_{in} \sim 10^{-2}$ and under this condition with the previous values of E_o and L we would fall more into the regime described by (12b).

In eqn. (12b) ν_{in} enters only as the square root and at high altitudes $\nu_{in} < 1$; consequently, its smallness is felt less in the growth rate. For example, $\nu_{in} = 10^{-2}$ still provides a growth rate, $\gamma = 0.1(cE_o/BL)^{1/2}$ i.e., one-tenth the usual gradient drift growth rate. This would still result in rapid striation formation as seen by Pongratz and Jeffries [1977] with their parallel injection 450 km altitude barium releases (in these releases striations are seen to

form on the same time scale as the 200 km altitude type releases).

In summary, we have investigated the gradient drift instability for F region plasma clouds and find that there is a further delineation of the instability depending on whether ν_{in} is greater than or less than $4cE_0/BL$. In the former case, the growth rate is cE_0/BL, the usual $\underline{E} \times \underline{B}$ gradient drift instability; however, in the latter case the growth rate is $(cE_0 \nu_{in}/BL)^{\frac{1}{2}}$ and demonstrates the influence of ion inertia effects (ion inertia plays the role of collisions in this regime).

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